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Verification of harmful subsoil compaction in loess soils

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ABSTRACT

A Compaction Verification Tool (CVT) is presented to detect harmful subsoil compaction based on critical values of soil functions [saturated hydraulic conductivity $K_s = 10\ \mathrm{cm} \times \mathrm{d}^{-1}$ and air capacity (−60 hPa), $AC_{60} = 5$ vol%] to provide a soil protection tool for legislative purposes. Harmful subsoil compaction is defined as follows: if these two soil functions fall below their defined critical value (degradation class IV) and if the percentage of measured values achieves 10 to <25%, the soil is classified as "assumed harmful compacted". If the percentage is >25%, then the soil is classified as "verified harmful compacted". The concept is tested using Luvisols derived from loess. Single and multiple dynamic loadings were applied at field capacity using a tractor-pulled single wheel load frame with three loads (3.3, 6.3, and 7.5 Mg). Unloaded reference profiles and loaded ruts of experimental plots were analysed, horizon specifically, using undisturbed soil samples to detect changes in K_s and AC_{60} in the top- and subsoil. According to CVT, harmful subsoil compaction could be only determined for the 6.3 Mg load (13%, "assumed") and for the 7.5 Mg load (52%, "verified") at the 40 cm depth for the multiple wheel passes. However, significant load-dependent reduction of AC_{60} could be detected down to 60 cm (E- and Bt-horizon) for the 6.3 and 7.5 Mg loads, and for K_s down to 40 cm (E-horizon).

1. Introduction

In present-day industrialized agriculture heavier machinery leads to higher wheel loads on fields (Soane and van Ouwerkerk, 1994; Pagliai and Jones, 2002; Hakansson, 2005). With increasing size and weight of agricultural machinery, deeper subsoil horizons are subjected to higher mechanical loads resulting in negative impacts on soil functions (Horn et al., 2000). Van den Akker et al. (2003) stated that the ground pressure of agricultural machinery has more than doubled during the last three decades. This on-going trend of increasing machinery mass and size causes subsoil compaction, which remains an issue of concern in agricultural land management (Horn et al., 2006).

With regard to soil ecological functions, the degradation of the pore system due to compaction results in reduced or even zero oxygen diffusion (Hakansson, 2005). Filter and buffer qualities, infiltration, and groundwater recharge are reduced, along with an increased risk of erosion as well as perched water in topsoil horizons that diminish thermal diffusion (Fleige and Horn, 2000). Compaction has both agricultural and economic consequences. Intensive crop production with heavy machinery, especially under wet soil moisture conditions, affects crop performance and can cause yield losses. Therefore, profits are decreased (Ehlers et al., 2000; Hamza and Anderson, 2005). Subsoil compaction is regarded as an essential problem, because it is considered as permanent and the pore functions are not recoverable after their deterioration or alteration.

On scientific and policy level, compaction is already perceived as a serious ecological as well as economic problem. Officials in Europe are discussing how protection can be accomplished and need to know which data are relevant for risk assessment (e.g., Jones et al., 2003; Van den Akker et al., 2003; Eckelmann et al., 2006; Horn et al., 2006). The European Commission passed a mechanism (cross compliance) that links direct payments to compliance by farmers. Since 2005 arrangements concerning prevention of soil erosion, preservation of soil organic matter content, and other environmental standards are inspected and thereby connected to payments of environmental bonuses. Non-compliance of the standards leads to curtailing of the bonus payment. At a national level, e.g., in Germany, the ratification of the German Federal Soil Protection Act occurred in 1998. The act is directed to the farmers themselves and requests (1) a site-adapted land use with an obligation of precaution towards soil compaction and (2) the obligation to prevent "harmful changes of the soil" (Horn and Fleige, 2009). For the implementation of legal soil protection regarding the threat of subsoil compaction and the legitimation for legal action against harmful mechanical loading, there is a need for verification of load-induced negative impacts in the soil, which can be used as legal evidence.

To prevent subsoil compaction, the susceptibility of the soil can be determined using the *precompression stress (Pc) concept*, which

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compares soil mechanical parameters and the stress impact of machinery (Horn and Fleige, 2003; Zink et al., 2010). Not exceeding the Pc is the best protection to avoid compaction. Following this condition, a site-adjusted farming is always warranted. If the Pc is exceeded under the current land management it has to be decided whether or not the impact on the soil is harmful and has to be prevented by law.

A load impact can be expressed by the impairment of soil functional parameters (e.g., K_s, AC_{60}, ρ_b, Pc, air conductivity, and infiltration rate). To define, if the impairment of one or more parameters has harmful consequences for crop growth, several authors determined critical values for each parameter (Flühler, 1973; Glinski and Stepniewski, 1985; DVWK, 1997; Werner and Paul, 1999; Lebert et al., 2007). Horn and Fleige (2009) summarized some of these general proclaimed *critical values* to verify damaging subsoil compaction in relation to crop production (see also FEA, 2004). They differentiated a number of soil physical parameters with low and high indication, which are related to the functionality of the soil structure. Parameters such as penetration resistance or ρ_b were assigned with low indication to subsoil compaction, because they give no information about the condition of the pore system (Horn and Kutilek, 2009). Functional parameters such as air capacity, saturated hydraulic conductivity, or air conductivity were considered highly indicative. For the assessment of subsoil compaction, Horn and Fleige (2009) recommended that two parameters with high indication have to fall below their defined critical values. If this happens the subsoil is classified as having harmful compaction. Based on their statements, two highly indicative parameters [(1) air capacity (AC_{60}) with its critical value of <5 vol% for non-hydromorphic soils and (2) saturated hydraulic conductivity (K_s) with its critical value of $<10\ \mathrm{cm\ d^{-1}}$] were chosen and considered together in a tool for the verification of harmful subsoil compaction. K_s was chosen as functional parameter, which measures the mass flow of water and reflects, beside of the pore size, also the connectivity of the pore system. This parameter is important for infiltration and groundwater recharge and linked to negative environmental impacts including off-site damages due to soil movement by water erosion and leaching processes into surface water and ground water (Fleige and Horn, 2000). AC_{60} as a capacity parameter was chosen to express the pore size distribution and oxygen diffusion capability, which is important for the soil aeration, the root growth and the crop performance (Glinski and Stepniewski, 1985).

The objectives of the present study are (1) to determine load-induced changes of AC_{60} and K_s in top- and subsoil horizons of Luvisols in different weighted agricultural wheel traffic field experiments (loads of 3.3, 6.3, and 7.5 Mg) and (2) to introduce and test the Compaction Verification Tool (CVT) to determine if it can detect harmful subsoil compaction based on two critical values and, consequently, might be used as a legislative tool to protect the soil.

2. Materials and methods

2.1. Study area and field experiments

The loading experiments and samplings took place on Luvisols (IUSS World Reference Base, 2007) in the province of North Rhine-Westphalia (NRW) in the north-western loess region of Germany. The investigated Luvisols are characterized by texture class of SiL (FAO, 2006) (clay content of the Ap- and E-horizon is 13–16%, Bt-horizon starting at 50 cm contains 17–21% clay). Loess Luvisols enfold circa 15% of the area of Germany (Düwel et al., 2007). These soils are considered as highly fertile, arable land and susceptible to mechanical loads.

The wheeling experiments were done with three different wheel loads (3.3, 6.3 and 7.5 Mg). Tire inflation pressures ranged between 160 kPa (3.3 Mg), 250 kPa (6.3 Mg), and 350 kPa (7.5 Mg). The loadings were conducted in early spring and late autumn at soil moisture contents close to field capacity. A tractor-towed loading frame was used to apply the external loads. The load experiments were carried out without slip and smearing and simulated single and multiple (10×) passes of a wheeled vehicle. All loads were applied by radial tires with a width of 650/75 R32. For further details on specific site characteristics, the experimental setup of the wheeling experiment, and the results of stress propagation measurements, see Zink et al. (2010).

2.2. Sampling and laboratory measurements

All experimental plots ("loaded" four plots per load variant and "unloaded" two plots) were sampled by taking disturbed and undisturbed soil samples from three soil horizons (topsoil: Ap-Horizon: 0.2–0.25 m; subsoil: E-horizon: 0.4–0.45 m; Bt-horizon: 0.6–0.65 m). Loaded profiles were sampled in the rut. Grain size distribution was analysed from disturbed material using the sieve and pipette method according to Hartge and Horn (2009).

Undisturbed soil samples were used to determine total soil porosity (TSP), soil water retention (SWR), air capacity (−60 hPa; AC_{60}), and saturated hydraulic conductivity (K_s) (cylindrical cores of $100\ \mathrm{cm^3}$). The cores were taken vertically with five replications per depth for SWR and seven repetitions per depth for K_s. TSP was obtained gravimetrically by weighing the soil before and after drying at 105 °C for 24 h. SWR was determined at saturation followed by drainage of the samples using a combined ceramic vacuum and pressure plate outflow method (Schlichting et al., 1995). Proportion of pore size classes was estimated based on the water desorption characteristics (Hartge and Horn, 2009). K_s was measured by re-saturated samples using the hood permeameter method as described by Hartge (1966).

2.3. Statistical analyses

Statistical analyses were conducted using the open source software R version 2.6.2. Normal distribution was tested using the Shapiro Wilk normality test and quantile comparison plots. Significance of mean values was tested using the Tukey test with alpha level of 5%, which is displayed by small letters in the figures. Notches in box plots give roughly a 95% confidence interval for difference in two medians (Mc Gill et al., 1978). Percentages of degradation classes considering the different load situations were estimated by calculating the probability of AC_{60} and K_s falling below their critical values. Probabilities were calculated using empirical distribution functions, in which the percentages of degradation classes comply with the estimated cumulative relative frequencies for each parameter [class I: $P(K_s \geq 10\ \mathrm{cm\ d^{-1}} \cap \mathrm{AC} \geq 5\ \mathrm{vol\%})$; class II: $P(K_s \leq 10\ \mathrm{cm\ d^{-1}} \cap \mathrm{AC} \geq 5\ \mathrm{vol\%})$; class III: $P(K_s \geq 10\ \mathrm{cm\ d^{-1}} \cap \mathrm{AC} \leq 5\ \mathrm{vol\%})$; class IV: $P(K_s \leq 10\ \mathrm{cm\ d^{-1}} \cap \mathrm{AC} \leq 5\ \mathrm{vol\%})$].

2.4. The Compaction Verification Tool (CVT) – a tool to verify load-induced harmful soil degradation

Fig. 1 shows the concept for verification of *harmful* subsoil compaction ("Compaction Verification Tool", CVT). The concept is based on measurements of soil functional parameters K_s and AC_{60} and their classification using their critical values, proposed by FEA (2004) and Horn and Fleige (2009). The percentage of measured values allows a horizon-specific quantification and assessment of the compaction impact on the (sub) soil under different load situations.